Remote, Aerial, Trans-Layer, Linear and Non-Linear Downlink Underwater Acoustic Communication

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***Abstract*-Both the linear mechanism for optical to acoustic energy conversion are explored for opto-acoustic communication from an in-air platform to a submerged vessel such as a submarine or unmanned undersea vehicle. This downlink communication can take the form of a bell ringer function for submerged platforms or for the transmission of text and/or data. The linear conversion mechanism, also known as the linear opto-acoustic regime where laser energy is converted to sound at the air-water interface, involves only the heating of the water medium. In this mode of operation, the acoustic pressure is also linearly proportional to the laser power. In contrast, the non-linear conversion mechanism, also known as the non-linear opto-acoustic regime where focused laser energy is converted to sound at the air-water interface, involves a phase change of the water medium through evaporation and vaporization which leads to the production of a plasma. In this mode of operation, the acoustic pressure is non-linearly related to the laser power. The non-linear conversion mechanism provides a more efficient, i.e. higher source level, yet less controllable method for producing underwater acoustic signals as compared to the linear mechanism.**

A number of conventional signals used in underwater acoustic telemetry applications as well as command and control applications are shown to be capable of being generated experimentally via the linear and non-linear opto-acoustic regime conversion process. The communication range and data rates that can be achieved in both conversion regimes are addressed. The use of oblique laser beam incidence at the air-water interface to obtain considerable in-air range from the laser source to the in-water receiver is addressed. Also, the impact of oblique incidence on in-water range is examined. Optimum and sub-optimum linear opto-acoustic sound generation techniques for selecting the optical wavelength and signaling frequency for optimizing in-water range are addressed and discussed. Opto-acoustic communication techniques employing M-ary Frequency Shift Keying (FSK) and Multi-frequency Shift Keying (MFSK) are then compared with regard to communication parameters such as bandwidth, data rate, range coverage, and number of lasers employed. In the non-linear conversion regime, a means of deterministically controlling the spectrum of the underwater acoustic signal has been investigated and demonstrated by varying the laser-pulse repetition rate to provide M-ary Frequency Shift Keyed signaling. This physics-based conversion process provides a methodology for providing low probability of intercept signals whose information is embedded in noise-like signals. These laser generated signals can then be used in a frequency hopped spread spectrum technique with the use of the proper receiver structures to take advantage of the frequency diversity and periodicity inherent in this type of signal structure that could also be used to combat frequency selective fading in underwater acoustic channels.

I. INTRODUCTION

Communicating with an underwater platform such as a submarine operating at speed and depth while in the air, without penetrating the water surface, would increase the autonomy and flexibility of subsurface, surface and aerial platforms engaged in undersea warfare and could have a variety of commercial and oceanographic applications. There is an increasing need to link in-air assets with in-water assets with the advent of unmanned undersea vehicles (UUVs) and unmanned aerial vehicles (UAVs). These new technologies and capabilities require novel communication methods in order to be integrated into a fully netted environment that is increasingly required to address current and emerging mission areas. The novel laser systems presented in this paper address these needs.

Acoustic energy propagation is efficient in the water environment, whereas RF or optical energy propagates well in air. Historically, acoustic transducers are used to detect or generate underwater acoustical energy and form the basis of modern day sonar systems. However, the transducers must be physically immersed in the water environment for efficient transmission and reception of acoustic sound pressure. The air-water boundary poses additional constraints on methods for communication between underwater and surface or in-air platforms. Typically, remote Radio Frequency (RF) systems are deployed by underwater platforms as a means of communication with platforms above the water surface.

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As demands for higher data rates and improved battlespace connectivity increase while maintaining platform stealth at speed and depth; RF communications, employing buoys or Unmanned Undersea Vehicles (UUVs) will prevail over slower acoustic communication schemes.

An alternative approach is presented that exploits the interaction of light and sound at the water surface. This scheme uses acoustic signals in the underwater environment and optical energy in the air to achieve a bi-directional communication link across the air water interface. Information from the sound field in the water is detected using a laser interferometer to measure the velocity of the surface vibrations caused by the underwater sound propagating to the water surface. This acousto-optic scheme discussed in prior publications [1,2] converts the underwater acoustic signal into a modulated optical beam in the air at the water surface. The counterpart of the acousto-optic sensing concept and the focus of this paper is the opto-acoustic transmission technique employed for a communication downlink. This opto-acoustic downlink communication technique provides a method for transmitting data from an in-air platform to a submerged platform at speed and depth via conversion of in-air optical energy into underwater acoustic energy at the air-water interface. The combination of these two technologies presents a means for aerial, remote, bi-directional communications across the air-water interface as shown in Figure 1.

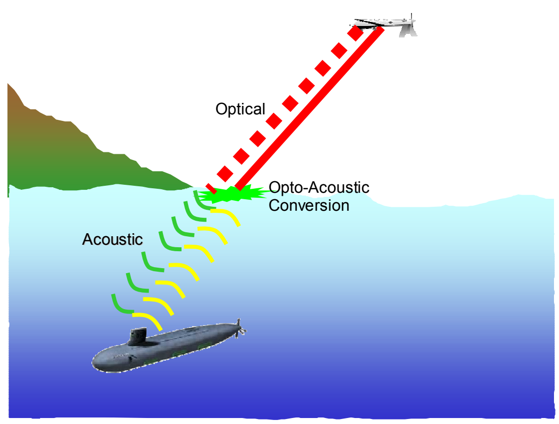

Figure 1. Remote, aerial bi-directional opto-acoustic communications concept.

This concept, although challenging, has application to FORCEnet, particularly undersea FORCEnet – the Navy's future vision for a fully netted battlespace, Communications at Speed and Depth (CSD), and also represents a unique Navy technology development. Together, the opto-acoustic transmitter and the acousto-optic receiver comprise a bi-directional communication link capability across the air-water interface that does not currently exist.

II. LASER-BASED ACOUSTIC TRANSDUCER

The opto-acoustic transmission technique for remote generation of underwater sound employs an in-air, high-powered, pulsed or continuous wave (CW) laser to transmit acoustic signals into the water. The opto-acoustic technique can be used for downlink communications to transmit data from an in-air platform to a submerged platform at speed and depth via conversion of optical energy into acoustic energy at the air-water interface. This opto-acoustic energy transfer mechanism can be subdivided into a linear regime and a non-linear regime on the basis of energy density within the medium.

In the linear regime, the laser beam incident at the air-water boundary is exponentially attenuated by the medium, creating an array of thermo-acoustic sources relating to the heat energy and physical dimensions of the laser beam in the water, thus producing local temperature fluctuations that give rise to volume expansion and contraction. The volume fluctuations in turn generate a propagating pressure wave with the acoustic signal characteristics of the laser modulation signal [3-8]. Therefore, a number of traditional acoustic communication signals such as frequency modulated sweeps also known as CHIRPs, Binary Phase Shift Keyed (BPSK), Quadrature Phase Shift Keyed (QPSK), Frequency Shift Keyed (FSK), and Multi-Frequency Shift Keyed (MFSK) signals can be created. Figure 2 depicts the opto-acoustic system block diagram including the modulator used for linear regime operation.

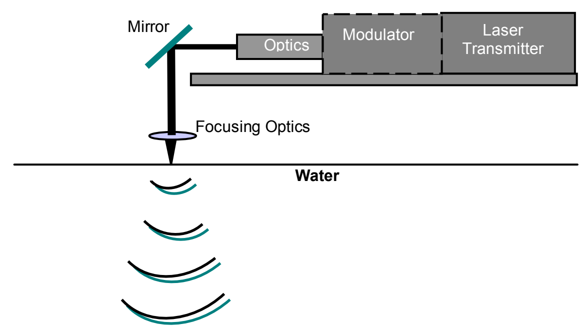

Figure 2. Opto-acoustic system diagram

The pressure spectral response as a function of range, the medium's parameters, laser beam parameters, and modulation parameters within the linear opto-acoustic regime is found by integration of the Green's function integral for the pressure release surface [8] to obtain the acoustic response at the in-water receiver location when the thermo-acoustic line array is known. The result of this integration is given in Equation (1) for normal laser beam incidence at the air-water boundary. The time domain expression for the pressure signal is obtained by taking the real part of the inverse Fourier transform of Equation (1).

$$P(\bar{r},\omega) = \frac{-TI_0\beta a^2}{2C_p}\frac{\exp(ikr)}{r}\frac{\omega^2\tau_\mu}{1+\omega^2\tau_\mu^2}\exp(-\omega^2\tau_a^2/4)I(\omega) \quad (1)$$

where

$$I(\omega) = \int_{-\infty}^{\infty} I(t)\exp(i\omega t)dt \ , \tau_\mu = \frac{\cos\theta}{\mu c}, \text{ and}$$

$$\tau_a = \frac{a\sin\theta}{c}.$$

The other parameters introduced in Equation (1) are defined in the following list of symbols.

T = optical transmissivity

r = range to observation point

k = acoustic wave number

ω = angular frequency

τ_μ = vertical characteristic delay time

τ_a = horizontal characteristic delay time

$I(t)$ = temporal laser waveform

θ = angle of observation from the vertical

$I(\omega)$ = spectrum of temporal laser waveform

I_0 = laser intensity amplitude = P_0/a^2

β = thermal coefficient of expansion

C_p = specific heat of the liquid

a = laser beam radius

μ = optical absorption coefficient

A Matlab computer model was constructed that examines the temporal and spectral character of the linear opto-acoustics regime for both normal and oblique laser beam incidence. This model has been used as a prediction mechanism in terms of heating geometry, pressure levels, and waveform character as a function of a multitude of medium and laser parameters such as sea state, sea surface slope, laser wavelength and optical absorption coefficient, and laser modulation frequency [8].

A number of laser sources can be combined to form a laser array source, i.e. a spatially periodic source that can be used for linear regime opto-acoustic communication. A laser array source can be used to increase the amplitude and directivity of the signal produced by a single laserm [7,8].

Oblique laser beam incidence provides a method to obtain increased horizontal in-air range from the laser source to the in-water receiver and also provides a method to control the in-water acoustic beampattern. The optimized in-water range coverage can be obtained by optimizing the signal frequency and the optical absorption coefficient for the particular conditions under consideration. The communication range may be increased under lower sea state conditions and/or with an increase in laser power. Using sub-optimum parameter choices for signal frequency and optical absorption coefficient result in a wider beampattern as compared to the practical sub-optimum parameter choices for signal frequency and optical absorption coefficient [7,8].

The acoustic signal level, data rate, and acoustic beampattern can be controlled through the appropriate use of multiple lasers that are properly spaced and time multiplexed. One set of lasers can be used to produce increased signal level while the other set of lasers can be used to increase data rate [7,8].

As the laser energy density is increased using short duration, high intensity, focused laser pulses as depicted in figure 2, a non-linear energy conversion process produces broadband transients with considerable acoustic energy in the water. The acoustic transients can be used to generate acoustic communication signals. In all cases, broadband acoustic transients with considerable acoustic energy are created. In ascending level of energy conversion efficiency, the phenomena are as follows: thermodynamic parameter changes, weak and strong surface evaporation as well as bulk evaporation in the media, and evaporation followed by optical breakdown (ionization) of the vapor material with subsequent cavitation bubble production [7,9-12].

The non-linear opto-acoustic regime has also been theoretically and experimentally examined. A novel method for creating a narrowband communication scheme from the linear superposition of wideband component shock and bubble waveforms was formulated, expressed theoretically, and simulated [7,12]. The general time domain expression for the pressure waveform as a function of range and vertical observation angle as given in Equation. (2) as

$$p(r,\theta,t) = P_m(r,\theta)\sum_{n=0}^{N-1}\exp\left[-\frac{(t-nT_R)}{\tau(r)}\right]u(t-nT_R) + \sum_j P_{Bj}(r,\theta)\sum_{n=0}^{N-1}\exp\left[-\frac{(t-T_{Bj}-nT_R)}{\tau_{Bj}(r)}\right]u(t-T_{Bj}-nT_R) \quad (2)$$

where

N = number of laser pulses

T_R = laser pulse repetition period

T_{Bj} = time delay between peak of plasma generated transient and peak of j[th] cavitation generated transient

$P_m(r,\theta)$ = peak pressure of plasma generated acoustic transient as a function of range

$P_{Bj}(r,\theta)$ = peak pressure of j[th] cavitation generated acoustic transient as a function of range

$\tau(r)$ = time constant of plasma generated acoustic transient as a function of range

$\tau_{Bj}(r)$ = time constant of j[th] cavitation generated acoustic transient as a function of range

The pressure time waveform as a function of range and observation angle consists of an optical breakdown pressure term followed by a summation of time-delayed, bubble cavitation generated pressure terms. Each pressure term is a scaled exponential acoustic transient. The magnitude of the corresponding acoustic pressure spectrum is given in Equation (3).

$$|P(r,\theta,\omega)| = \left|\frac{\sin\left(\frac{N\omega T_R}{2}\right)}{\sin\left(\frac{\omega T_R}{2}\right)}\right| \cdot \left|\left[\frac{P_m(r,\theta)\tau(r)}{1+j\omega\tau(r)} + \sum_j \frac{P_{Bj}(r,\theta)\tau_{Bj}(r)}{1+j\omega\tau_{Bj}(r)} e^{-j\omega T_{Bj}}\right]\right|. \tag{3}$$

The basic theory of operation for communication applications is to pulse the laser at a number of repetition rates thus creating various pulse trains to produce a unique set of narrowband comb function spectra, each of which contains tones at the laser repetition rate and its harmonics. The repetitive production of acoustic shock waves due to laser pulsation can be used to construct signals for communication use. The non-linear opto-acoustic conversion process in conjunction with the acousto-optic detection using the laser Doppler vibrometer has also been used to demonstrate the initial feasibility of a remote, aerial, laser-based bi-static sonar capability [13].

III. EXPERIMENTAL RESULTS

Basic and applied research and development have been performed to assemble and test the laser systems under various water surface conditions. Experimental results for the opto-acoustic method for generating underwater sound are presented first. Initial prototype hardware designs have concentrated on the selection of the high-energy laser used for the opto-acoustic transmitter to obtain an efficient optical to acoustic energy conversion to deliver a high amplitude sound pressure level signal into the water with a known spectral response. Additionally, the opto-acoustic transmission system requires a scanning and adaptive focus optical system to provide consistent operation on realistic ocean surfaces.

Opto-acoustic experiments were conducted at NUWC and at the University of Massachusetts Dartmouth's SMAST facility. These experiments have demonstrated the capability of producing acoustic communication signals via laser-based optical methods. The pressure levels that were generated agreed well with the Matlab computer model and are sufficient for producing useful levels at short to medium underwater communication ranges [7]. A procedure for M-ary FSK, linear opto-acoustic communication was formulated based on range requirements, data rate, useable bandwidth, and number of lasers. Various methods of range coverage optimization were formulated theoretically and simulated in software for the linear opto-acoustics regime. This optimization is based on medium parameters (ambient noise, acoustic absorption, and receive Signal to Noise Ratio), signaling frequency, laser beam incidence angle, and light absorption coefficient/wavelength [7].

Experimentally measured linear regime, laser-generated acoustic signals at modulation frequencies of 10kHz and 20kHz are shown in Figures 3a and 3b. This set of acoustic signals represents the ability to produce Frequency Shift Keyed (FSK) downlink communication signals.

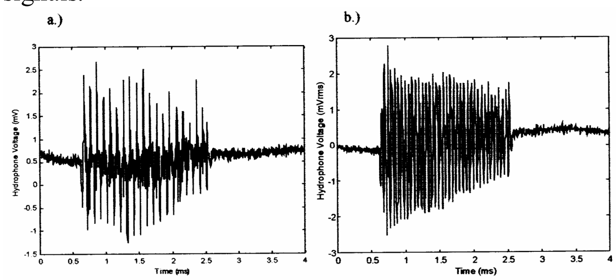

Figure 3. (a) 10kHz modulated, linear regime opto acoustically generated signal; (b) 20kHz modulated, linear regime opto-acoustically generated signal.

Large in-air distances can be covered by employing oblique laser beam incidence at the air-water boundary. The simulation results in Table I show a data rate and an in-water range comparison of M-ary FSK modulation versus MFSK Modulation for a modulation center frequency, f = 40kHz and an optical absorption coefficient of $\mu = 15.7\text{m}^{-1}$ corresponding to an optical wavelength of 1 micron. Table II simulation results show in-air and in-water range versus laser incidence angle at the air-water interface for a number of receiver vertical and horizontal observation angles in the water. Also shown are the main response axis and associated 3dB beamwidth of the laser-generated in-water sound as a result of the laser beam incidence angle and the receiver vertical and horizontal observation angles, illustrating the deterministic control of a number of key acoustic parameters.

The non-linear regime of opto-acoustic conversion is more energy efficient than the linear regime of optical to acoustic energy conversion since a higher percentage of optical energy is transformed into acoustic energy via the laser-generated plasma and subsequent water medium physical interaction [7,9-12]; but this method requires more complex signal control. The non-linear process can be employed to produce higher sound pressure level signals at potentially higher data rates. The repetitive production of acoustic shock waves due to laser pulsation can be used to construct signals for communications.

Each repetition rate represents a symbol in the communication alphabet.

Table I. M-ary FSK Versus MFSK Modulation Comparison

Modulation Method	Data Rate Bits/s	Bandwidth (kHz)	SPL (dB re 1μPa)	In-Water Range (Meters)
2-ary FSK	10	1	137	800
4-ary FSK	20	2	137	800
8-ary FSK	30	4	137	800
16-ary FSK	40	8	137	800
1-MFSK	10	0.5	137	800
2-MFSK	40	1	131	517
3-MFSK	80	1.5	128	410
4-MFSK	160	2	125	320

Note: Simulation is based on f = 40kHz and $\mu = 15.7\text{m}^{-1}$.

Table II. Practical Sub-Optimum Range and Angle Parameter Set (f = 40kHz and $\mu = 15.7\text{m}^{-1}$)

OBLIQUE INCIDENCE ANGLE θ_i (DEGREES)	VERTICAL OBSERVATION ANGLE θ (DEGREES)	HORIZ-ONTAL OBSERVA-TION ANGLE ϕ (DEGREES)	IN-WATER RANGE (METERS)	IN-AIR RANGE HORIZ-ONTAL/ SLANT (METERS)	SPL (dB re μPa)	OPTICAL TRANSMISS-IVITY	MRA (DEGREES)	3dB BEAMWIDTH (DEGREES)
0	85	N/A	926	100/100	139.8	0.98	85	10
53.6	52	0	937	136/169	140	1	52	6
53.6	83	90	937	136/169	140	1	83	9.5
80	42	0	820	567/576	137.8	0.75	42	7.5
80	82	90	812	567/576	137.6	0.75	82	10.5

Note:

The SPL is computed based on the peak level for each waveshape. Range is calculated based on a receive SNR of 10dB, spherical spreading, acoustic absorption, noise spectrum levels for sea state 3, and the noise bandwidth corrections based on the bandwidth of the waveshape.

These signals have the properties of temporal and spectral diversity and can provide frequency shift keyed (FSK), frequency hopped direct sequence spread spectrum (FH-DSSS), and discrete frequency modulated sweep capabilities. The data rate of this communication downlink can range from several bits per second up to several kbps based on the laser pulse repetition rate, modulation parameters, and sound pressure level requirements.

Figure 4 shows an acoustic shockwave, time waveform produced by a single, high-energy, short duration, laser pulse. The first pulse is the acoustic shock wave produced by optical breakdown of the water medium and the subsequent three pulses produced are due to several cavitation bubble collapse and expansion cycles [7,9-12].

This acoustic shock wave time series serves as the building block for generating spectrally controllable signals by varying the laser repetition rate. In addition, experiments in the non-linear regime have been conducted demonstrating increases in the acoustic source level, i.e. with a Sound Pressure Level (SPL) equal to 185dB re 1μPa generated in hydrostatic, fresh water conditions [12].

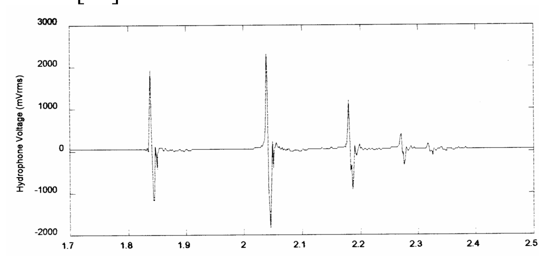

Figure 4. Non-Linear opto-acoustic regime, laser-generated acoustic signal from a single laser pulse.

An underwater acoustic signal generated with a laser repetition rate of 500 Hz is shown in Figure 5 [12]. The time series data shown in Figure 5a has three distinct non-linear opto-acoustic pulses with a maximum SPL of 184.91 dB_{rms} re μPa @1m. The 2 ms separation between pulses is consistent with a 500 Hz laser repetition rate. It was concluded that the buildup of a vapor cloud precluded subsequent acoustic signal generation following the third set of transients which would have further enhanced the desired spectral components. The spectral response is shown in Figure 5b. The desired components of the spectrum generated by laser pulse repetition are obscured due to modulation by the single laser pulse spectrum demonstrating destructive interference at non-coherent, low laser pulse repetition rates relative to the inter-transient delays shown in Figure 4. An enlarged view of the spectrum between 43 kHz and 47 kHz is superimposed in the top right corner of Figure 5b. A 500 Hz separation is observed between oscillations in the spectrum, correlated to the frequency of the laser pulse repetition. The simulated Fourier transform using a single experimental acoustic pulse spectrum multiplied by a scaled Dirichlet function using 5 pulses contained within 10 ms at a repetition rate of 500 Hz is shown in Figure 5c.

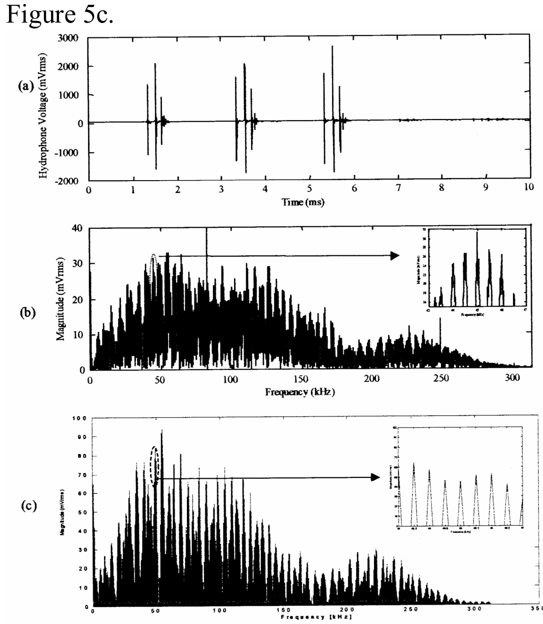

Figure 5. Plot of an underwater acoustic signal generated by focusing an infrared laser beam having a pulse repetition rate of 500 Hz onto the water surface, and captured by an underwater hydrophone showing detailed (a) time structure of the opto-acoustic transient; (b) Fourier transform; and (c) simulated Fourier transform.

This simulation demonstrates that in fact the spectrum shape and content can be modeled and is similar to that shown in Figure 5b as one might expect. An enlarged view of Figure 5c shows the 500 Hz tone separation clearly. The amplitude distribution compared to Figure 5b and the sharpness of the tones in Figure 5c

are due to the two additional pulses used in the simulation as compared to the experimental result that is degraded by the lack of these extra pulses.

It should be noted that deterministic secondary acoustic transients can be employed to provide an additional level of covertness for LPI applications. Short pulse laser systems in the femtosecond and picosecond regime exist that do not produce additional acoustic transients following the optical breakdown shockwave in water. It is possible to use two laser systems operating in the non-linear opto-acoustic regime with a known transient delay separation to obscure the in-water acoustic shock wave transmission thus obscuring the transmitted acoustic spectrum to unwanted receiver observation. In this mode of frequency hopped spread spectrum operation, additional signal processing can be applied to determine and highlight the dominant laser pulse repetition rate that is hidden and embedded in the signal for data transmission as opposed to the modulated and cluttered acoustic spectrum alone that appears noise-like and not well defined. This method of signal processing allows the transmit laser systems to reduce their transmit power and therefore their acoustic SPL to achieve LPI signal levels while still achieving downlink communication to an in-water receiver with knowledge of the repetition rate pattern and the superimposed pattern of secondary transients and their known modulated delays. Figure 6 shows a 10kHz laser repetition rate simulation example. Figure 6a and 6b show respectively the noise only time and frequency domain waveforms for comparison to figure 6c and 6d which show in the time and frequency domain respectively the laser-generated opto-acoustic signal at a signal-to-noise ratio (SNR) of –6dB. Figure 7 shows a plot of a signal detector output clearly indicating the presence above background noise of the transmitted symbol.

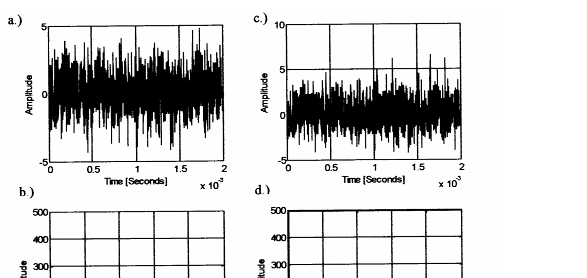

Figure 6. Plot of a simulated underwater acoustic LPI signal generated by focusing an infrared laser beam having a pulse repetition rate of 10kHz and a variable secondary laser pulse structure with controllable variable delay onto the water surface (a) time domain representation of noise-only case; (b) Fourier transform frequency domain representation of noise-only case; (c) time domain representation of –6dB SNR signal and noise case; and (d) Fourier transform frequency domain representation of –6dB SNR signal and noise case.

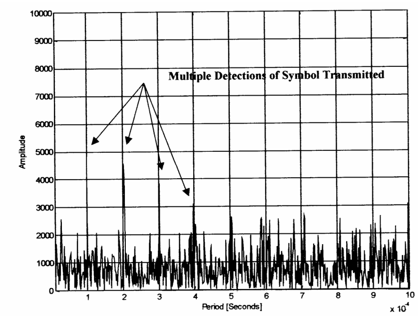

Figure 7. Plot of LPI opto-acoustic signal detection at a SNR=-6dB

IV. CONCLUSIONS

Laser-based methods for remote, aerial communications have been presented and demonstrated. Controlled laboratory tests for investigating the feasibility of linear and non-linear opto-acoustic signal generation were conducted under hydrostatic conditions. The highest measured SPL of the in-water acoustic transmissions was 185 dB re 1 μPa at a meter distance. It remains a challenge to provide high frequencies and associated high data rates in the non-linear opto-acoustic regime due to the difficulties of dithering the position of the laser beam on the water surface to mitigate vapor build-up. However, a combination of short laser pulsing systems that mitigate both vapor production and cavitation related shock waves and a fast, intelligent laser dithering system can be used to overcome these challenges.

These opto-acoustic and acousto-optic technologies have been demonstrated to provide initial feasibility and show great promise for use in a number of applications such as bi-directional underwater acoustic communications (tactical paging for submarines and increased two-way gateway functionality without a surface buoy expression) and active aerial sonar. These methods employ non-contact, covert optical methods to provide greatly enhanced sensor, communications, and sonar capability that do not currently exist. The opto-acoustic technologies offer a solution to mission problem areas such as for greatly enhanced battlespace connectivity from submerged platforms to in-air platforms in the area of stealth and also in murky or deep waters where LIDAR does not function due to insufficient optical energy return as a result of the increased round trip optical attenuation in turbid water. The critical engineering development areas necessary to demonstrate these systems on ocean surfaces are continuous acousto-optic operation with sea surface roughness and adaptive focusing/steering laser beam control optics for both laser systems.

This remote, aerial, laser-based trans-layer, communication technology provides a revolutionary and transformational capability that provides the U.S. Navy with a level of battlespace connectivity and awareness

that does not exist today. This capability, once the inherent challenges have been overcome, can be transitioned and integrated in order to augment our warfare edge and to move forward with agile above surface and undersea FORCEnet and CSD concepts.

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